ITALIAN EXPERIENCE AND PROBLEMS IN DEEP GEOTHERMAL DRILLING*

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*Published Only

ABSTRACT

Geothermal exploration at depth is being conducted in the Larderello area of Italy, in order to ascertain whether it is possible to extract geothermal fluids from the layers which underlie the reservoir now being exploited.

The main operating problems are caused by the high thermality and the chemical corrosiveness of the fluids encountered; and by the practical problems involved in drilling without circulation to the surface in mainly hard but anhomogenous fractured formations.

The technology employed for deep geothermal well drilling plays an important role in this research.

In deep geothermal well drilling it is essential that the equipment and the materials employed are suitable for use in areas which are characterized by high thermality and chemical corrosiveness.

The results of the experiences gained in Italy concerning the materials and tools employed in deep geothermal exploration are presented.

The various problems involved are described in detail and particular mention is made of drift control, fishing operations, cementation of the deep casing, control of the circulation fluid, and choice of the tubular materials.

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1. Introduction

Geothermal activity in Italy is now directed partly at exploring new areas and partly at recovering fluids with better thermodynamic characteristics from the traditional geothermal areas. For the latter reason the Tuscan geothermal areas are now the subject of a deep drilling programme which is aimed at individuating, below the reservoir exploited at present, geological horizons whose lithological characteristics are such as to guarantee the presence of hydrothermal circuits.

A seismic survey of the Larderello area individuated a deep reflecting horizon that varies between 3500 and 7000 m depth. At the moment, however, "deep research and exploration" is used in reference to wells that are 3000-5000 m deep. The objectives set for these wells are:

a) to verify whether, at technically feasible depths, there are permeable horizons capable of forming a second reservoir of industrially exploitable endogenous fluids;

b) to improve the hydrogeological model of the field for a more rational exploitation of the resource;

c) to evaluate the geothermal potential in terms of "resource" and "reserve", to a depth of 5 Km;

d) to study the possibility of recharging the field artificially by injecting water to great depths.

These objectives are attainable if the deep wells can guarantee:

- exploration of the deep horizons with wide diameters capable of providing significant data on their productive capacity;
- isolation of any reservoirs encountered in shallower horizons.

We must draw attention to the difference in interpretation or rather in definition of the concept "deep drilling" between Larderello and other geotermal wells. At Larderello the deep wells represent part of a deep research programme directed at investigating below the present exploited reservoir.

These are exploratory wells drilled to isolate the first reservoir and reach any other productive horizons between 3000 and 5000 m deepth. In the other geothermal fields, generally speaking, these wells are for exploiting the first known reservoir and drilled at less depth.

The stratigraphic sequence expected in these wells in the Larderello zone is, approximately:

from 0 - 500 m:	cover formations, comprising Neogenic sediments and flysch facies allochthonous complexes of a mainly clayey-carbonate composition.
from 500 - 1000 m:	complex forming the so-called "first reservoir", consisting of limestones and the Mesozoic Anhydritic Series. These are highly fractured formations.
below 1000 m :	Triassic-Paleozoic schistose-quartzitic basement, made up of schists, quartzites, micaschists, amphibolites and gneisses. These rocks are also rather fractured.

In view of the objectives of the programme and the geological situation in the area, the technical profile of these deep wells is usually that shown in Fig. 1. That is, the cover formations are lined with an 18"5/8 casing; the first reservoir is isolated with the 13"3/8 casing to 1500 m; the first part of the schistose-quartzitic basement is lined with a 9"5/8 casing to 3000 m. The last stretch of the bore remains uncased, with a diameter of 8"3/8. Depending on well conditions a 7" liner can be inserted in the last sector of the bore and joined to the 9"5/8 casing with a hanger.

2. Drilling practice

Deep geothermal drilling usually proceeds swiftly and routinely down to 3000 m. Beyond this point certain problems may arise, either due to the type of terrains crossed, which may be hard, unhomogeneous or of complex attitude, or to the high temperature conditions. The major difficulties stem from the fact that drilling nearly always has to proceed without return circulation, a consequence of the large number of unproductive fractured horizons that are practically impossible to seal.

The 13"3/8 casing, lowered at 1500 m, isolates the fractured zones of the anhydritic series and of the top of the schistose-quartzitic basement, However, fracturation quite frequently continues down into the underlying zone (see Fig. 2) so that drilling is conducted in very adverse conditions. The main problems are met in:

- drift control
- fishing operations
- cementation of the deep casings
- control of the circulation fluid
- choise of the tubular materials

2.1. Drift control in deep wells

One of the major operating problems while drilling these wells is that of controlling their drift, as they are extremely prone to deviation and the formation of terrible dog-legs.
The geological formations are responsible for this phenomenon. The terrains of the schistose-quartzitic basement vary in lithotype from schists to quartzites and gneiss. These rocks have undergone several different tectonic events that have created fractures, filled to varying degrees with secondary minerals, and faults. The stratification planes are consequently tilted by a few to a few tens of degrees.
In these conditions even a small load on the rock bit, in an attempt at drilling at a reasonable rate of 1-2 m/h, has a negative effect on bore verticality.
Only a very rigid stabilization of the drill-stem can reduce the risk of drift and doglegs.
An extremely rigid drill-stem, on the other hand, could endager the well itself, should some part of the stem break down, especially when water is the circulation fluid. In these circumstances the water is such a poor carrier that the debris in the bore takes no time to fall to the bottom and block the fish. At that point some long, laborious fishing operations are required, as the stabilizers complicate the work of cleaning the fish.
Drift control is also made difficult by a lack of instrumentation for measuring tilt and direction in very extreme temperatures.
ENEL has now decided to solve the problem by designing and constructing its own instrumentation for measuring inclination and direction in the presence of temperatures of 250 °C and pressure of 500 bar.
These studies will be based on past experience in constructing similar instrumentation for measuring temperature and bore diameter.

2.2. Fishing operations

These operations are considerably hindered by the high temperatures in the wells, which exclude the use of classical techniques; the latter would, in fact, solve such problems in a relatively fast and economic manner.
Certain well conditions would require the use of explosives and hydraulic equipment, or parts that are not resistant to high temperatures (back-off,hydraulic jars, bumper subs, turbines, impression block, etc.). In these circumstances one must fall back on more simplified and less efficient mechanical devices or, for example, undertake time-consuming, hazardous unscrewing of the pipes within the bore, using a left-hand drill-string.
When, as sometimes happen, it is no longer economically worthwhile recovering a fish, the side-track technique is used to unblock the well. However, the high temperature conditions may preclude the traditional system for this technique, which consists of a support cement plug and turbine with bent sub. Our alternative, in this type of operation, is to use a special permanent whipstock fitted with a stalk of some casings, so as to join the equipment to the underlying the pipes of the fish. The whipstok is blocked by pumping barite bentonitic mud of high density.
Technical measures of this type are frequently resorted to when the specialized market is unable to provide the necessary equipment and material for geothermal drilling.

2.3. Cementation of deep casings

Cementation of the casings in deep geothermal wells is one of the most complicated drilling operations. Intense rock fracturation causes serious problems in filling the annulus, added to which are the temperatures that affect the behaviour of the slurry.
Various methods have been developed for attaining the good cementation required in deep wells only partly filled with water, as a result of circulation losses.
Cementation is consequently a laborious task carried out in several phases using the more suitable technical systems and equipment for obtained the completed filling of annulus.
The first step is to cement the casing from the bottom up to the fracture, injecting large quantities of partly thixotropic slurry of low density from the bottom upwards. A duplex cement float shoe

or collar is used, for operating with a Duplex tubing seal nipple and drill-pipe.
The employed slurry consists of an unretarded cement obtained by intergrinding a basic clinker and active silica; the density is about 1.850 kg/l. As water sometimes has to be used as a drilling fluid the filtrate reducer is added to prevent dehydration of the slurry because of the lack of an adequate mud cake.
The casings are at such great depths, even 3000-4000 m, and the temperatures so high, that the pumping times have to be guaranteed by a retarder, which is added to the cement in suitable concentrations.
The composition of the slurry is studied in the laboratory by means of simulation tests, not scheduled in API standards, reproducing the setting conditions of the slurry in the bore.
This applies to both the setting pressure and the increase in temperature with time.
On the site the slurry is prepared in tanks beforehand to ensure the mixture is homogeneous.
If possible, cooling circulation at well-bottom during setting of the slurry prevents excessive retrogradation of the mechanical properties which occur when slurry sets in high temperature enviroments (Fig.3).
The second stage can be approached in various ways. The annular space from the fracture to the surface can be filled by placing a full opening multistage cementer above the fracture, isolating if necessary the fracturing space with an external casing packer in the higher anulus. Where there is more than one fracture this operation can be repeated, perhaps even shooting into the casing to create injection holes for the slurry; the top of the previous cementation is individuated beforehand by means of a log. The slurry used for these operations must be specially prepared each time, adding retarders, filtrate reducers and lightening materials as felt-necessary.
In place of the external casing packer one could inject an extremely clogging mixture through the full opening multistage cement (sodium silicate in brine environment); this mixture will temporarily plug the fracture and keep the slurry within the overlying annulus.
In other situations the second step will consist of injecting down into the empty annulus, in various stages if necessary. The slurry in this case can be preceded by a given thixotropic volume spacer which, due to the load loss ensuing from pumping this mixture,with high flow rates slows the slurry down and creates a more uniform distribution.
The success of cementation depends on whether the cementing shoes and float collars are able to operate satisfactorily in the high tem

perature environments.
These tools are chosen on the basis of the materials used in their construction; the strength and resilience properties, along with the thermal expansion coefficients, should be compatible in high temperatures and ensure that they are able to operate efficiently together in the maximum temperatures of well-bottom.
In the very deep wells we preferred to use the cementing shoes with float valves, which have a metal-metal contact seal and cast-iron back-up valve.
However, these shoes present more milling problems than the other types. The stab-in float collars gave excellent results even at 3000 m and with temperatures of more than 200 °C.

2.4. Control of the circulation fluids

As an alternative to drilling with water and no return circulation in the schistose-quartzitic formations of the basement we have sometimes conducted tests with air as circulation fluid. The advantage in this case is, first of all, to avoid the problem of finding the immense quantities of water (up to 100 m^3/h) needed during drilling without return circulation.
However, the well must be very dry for drilling with air only.
The circulation system could be assisted by a contribution of steam, as long as it is dry. The steam flow-rate must, at all events, be rather small, or problems will arise during extraction and insertion of the drill-stem.
We have very rarely encountered optimum conditions in the deep geothermal wells for air-drilling. The intensely fractured formations cause a reduction in the rising velocity of the air, thus reducing the system's flow capacity. On other occasions a very small quantity of water or wet steam may come from the fractured formations. In such cases the debris produced by the bit is not removed fast enough and accumulates at well-bottom in a slushy phase, preventing the bit from cutting into the virgin rock. The foam agents used in such high temperature environments are not always able to solve this problem.
When a total loss of circulation occurs in routine drilling with mud or water a certain hydrostatic level stabilizes in the well. This must be removed before beginning air-drilling. When this water is being removed, however, there is sometimes a strong and continuous flow of water from the surrounding formations, so that the operation

cannot be completed, or not immediately. Drilling must then continue with the air-water circulation system, regulated to curryng ratios. The well conditions, however, are not always suited to drilling with a lightened fluid, especially as regards depth, diameter, elevation of the hydrostatic level and the fracturation system. In order to use this fluid its density must be reduced until the level reaches the surface. To attain this so much air must be injected that, instead of having one lighter fluid only, we produce two dynamically unstable phases (water and air) that may lead to a loss of the air phase along the fracturations and even to uncontrolled blow-outs.

Where mud drilling is possible or advisable the fluids used must have a rheological stability and filtration characteristics that guarantee optimum operating conditions in high temperature environments.

The muds that have proved successful in prolonged working conditions of up to 200 °C have a bentonitic base dosed with a synthetic resin and chromolignite. The resistance can be improved, especially for higher temperatures, by adding products such as a synergesic blend of selected polymers.

Good results up to 250 °C were obtained with bentonitic and asbestos-based muds, activated with chromolignite and polycrylates, with or without the polymeric products, and with synthetic resin and caustic soda.

A similar success was also attained with the sepiolite and bentonite-based muds, using a small amount of the bentonite and the same additives mentioned above, although they do tend to develop rather strong gels in static, high temperature conditions.

Finally, oil or a colloidal suspension of sized asphaltic solids in water or in diesel-oil can further improve stability, even in higher temperatures than those described above.

The efficiency of the above mud systems can, of course, be improved by attending to a few practical matters, such as replacing any water lost by evaporation, cooling the fluid in special towers, stirring the fluids continually in tanks fitted with electric agitators and guns.

2.5. Tubular materials

2.5.a Drill -pipes

Operative conditions in deep geothermal wells have proved to cause greater stress to the drill-pipes than in the wells exploring the shallow reservoir. This stress is tied to both mechanical and chemical factors.
The increased mechanical stress can be attributed to:

- the greater depths and, consequently, longer drilling times;
- the difficulty in controlling the direction of deep wells, which has lead to a frequency of dog-legs.
- increased length of the upper section of the bore, diameter 16".

This interval is, in fact, so wide that the bit continually jumps within the pipe or is suddenly blocked, causing serious torsional stress.
The chemical stress, on the other hand, is mainly the result of having to use the condensate from the power plants as a drilling fluid, where there is no return circulation, because of the chronic water shortage in the Larderello area.
The G 105 grade drill-pipes have proved ideal for resistance to the above-mentioned mechanical stress, at least in the deep wells drilled so far. These same pipes have however undergone frequent anomalous breakages that are blamed on chemical stress as described above.
These breakages occur in the tool-joints, with no signs of damage to the body of the pipes. The tool joints we used are constructed in the following materials: 38 NC D4, AISI 4137. Breakage seemed to occur more often in the bottom pipe-lines, starting on the inside surface of the tool-joint.
These phenomena were so serious it was decided to run a series of tests simulating well conditions to define the phenomenology of the attack and attempt a solution to the problem.
The preliminary results confirm that the chemical attack is further aggravated by the existing temperatures.
An attempt is now being made to solve the problem either by using other materials for the pipes or by dosing the drilling fluid.

2.5.b Casing

The criteria followed in designing the deep geothermal wells at Larderello are that the diameters used to explore the deep reservoir should be wide enough to attain satisfactory productivity values despite the greater depth of borehole required.
The various casings are lowered not only to strengthen the bore walls but also to isolate the formations of the shallow reservoir. Cementation of the column is therefore an arduous operation and not always an absolute success.
This outcome had already been foreseen when drawing up the drilling programme and it is felt that the best results would only be achieved by adopting ideal criteria for the design of the casing.
At the same time we aware that the higher temperatures of the deep wells and their relatively longer drilling times would create quite serious thermal stress to the casing.
Consequently great care is taken in designing the casing to avoid breakages that would compromise completion of the well.
The results of the first drillings would appear to validate the criteria chosen.
These criteria include the use of API pipes with Buttress joints.
The thickness and grade of the steel are chosen after detailed analysis of the thermal stress and of the resistance of the materials.
Casing design is based on the results of lab tests to determine the tensile strength of J55, C75, N80 and P110 steels, cited in the American Petroleum Institute standards, at temperatures of 200 °C, 250 °C, 300 °C and 350 °C.
These results(Fig. 4 shows those for the N80 steel) were used to introduce a'reduction factor of the tensile properties'in the project design of the casing.
This factor was used empirically to evaluate, as a function of the maximum foreseeable temperature, the collapsing and crushing strength of the casing, beginning with the API data for environmental temperatures.
An impeded thermal expansion causes anomalous compressive stress to the geothermal casings.
The resistance characteristics of the buttress joints when undergoing these stresses are not given in the API standards. They were therefore the subject of a specific study carried out by ENEL on buttress joints of diameters 13"3/8,9"5/8 and 7".

The results are used in the design phases. The design criteria, as mentioned before, seem satisfactory and, together with a careful control of the quality of the materials and of the joint-make up, can prevente any damage to the casings used so far in the deep geothermal wells.

3. Conclusions

The deep exploration programme for the Larderello area is now in its first stage of development. The activity carried out so far has presented us with new problems in terms of operating methods and equipment.

It became immediately clear that the first priority was to devise an adequate technology for deep drilling, with the result that this is now one of the objectives of the deep drilling programme itself.

The solution to the problems outlined above lies in the construction of equipment and instruments designed specifically for the geothermal field.

Particular attention is paid in this respect to perfecting the methods and materials for controlling drift, for a more extensive use of air as a circulation fluid and for alleviating any eventual fishing operations.

The casings and drill-pipes of the geothermal wells are subjected to extreme mechanical stress and corrosion. The studies and research being undertaken in this sector should contribute greatly to the success of deep exploration.

It is clear from what we have just said that the work times and costs involved in this first phase cannot be held representative. However, there is no doubt that this type of research is a heavy financial commitment.

Nevertheless, the objective remains that of optimizing the technical aspects of drilling and to reduce as much as possible the drilling costs.

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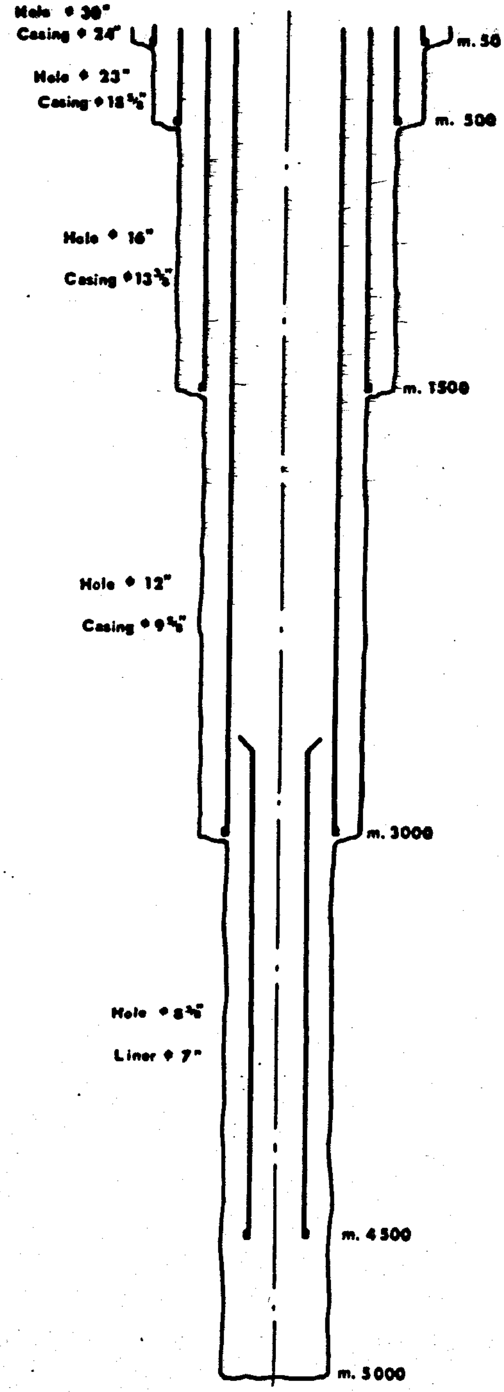

Fig. 1 – Typical technical profile of the Larderello deep wells. These are used at Larderello to explore the layers between 3000 and 5000 m.

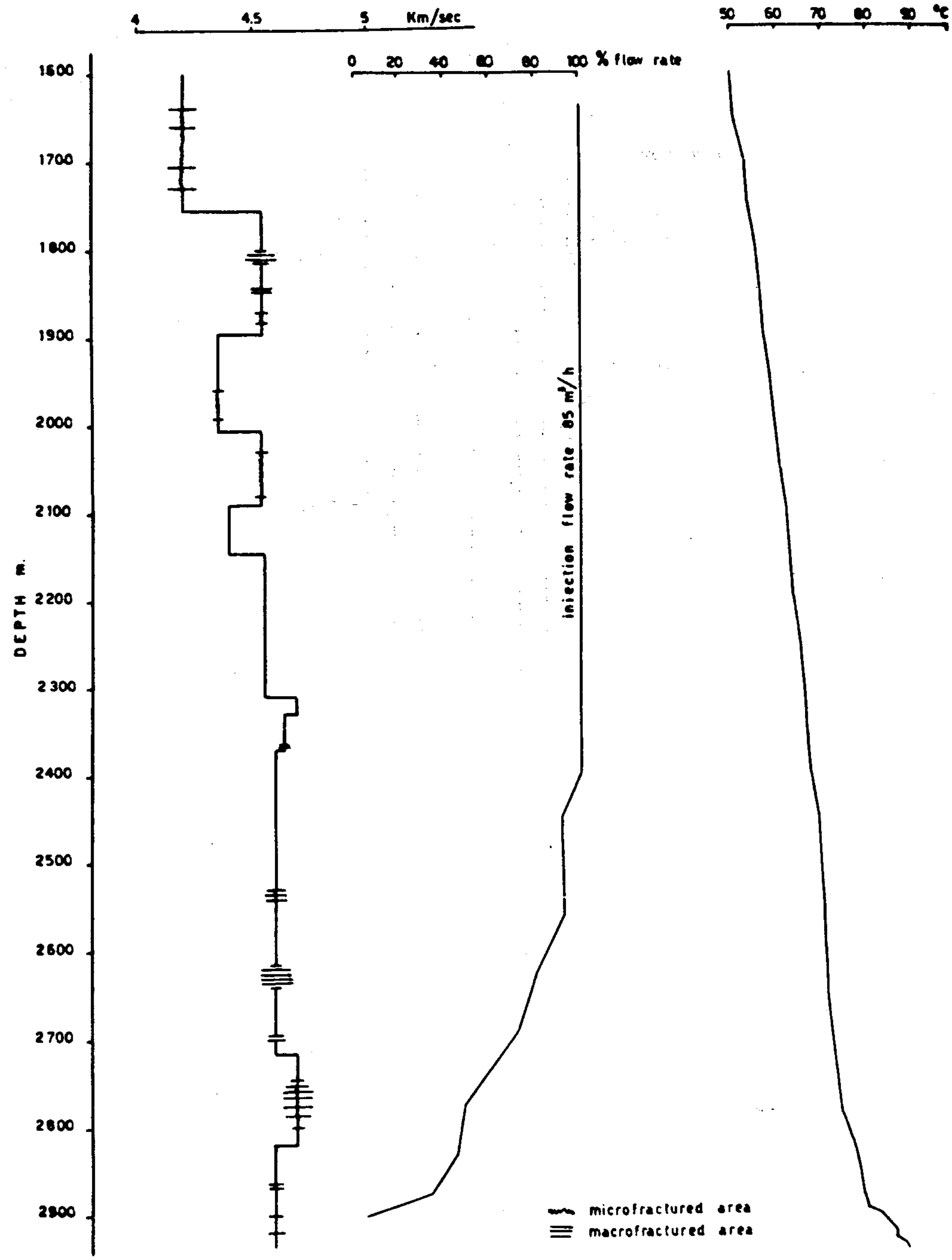

Fig. 2 - Diagram 1: Sonic log of the layers forming the exploited reservoir.

Diagram 2: Injectivity log of the layers forming the exploited reservoir (injected flow-rate: 85 m^3/hr).

Diagram 3: Temperature log run during the injection test of diagram 2.

Note the exstent of the fractures that are so difficult to isolate.

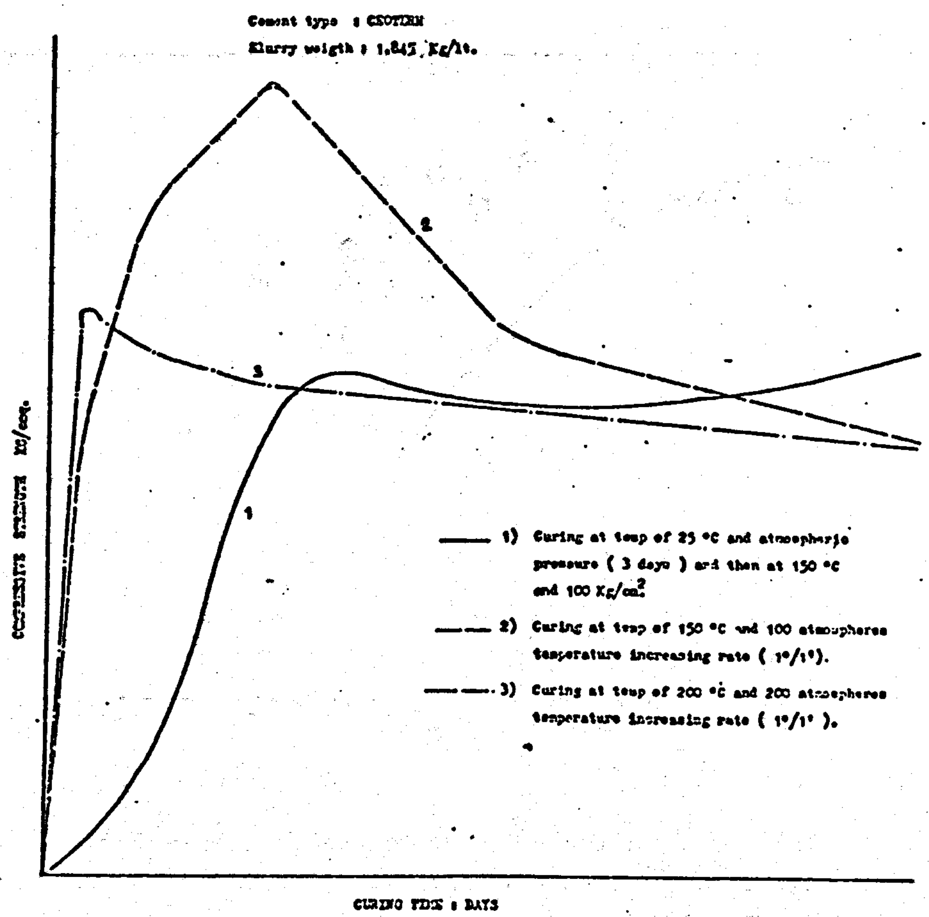

Fig. 3 - Compressive strength of a slurry curing at simulated well condition.

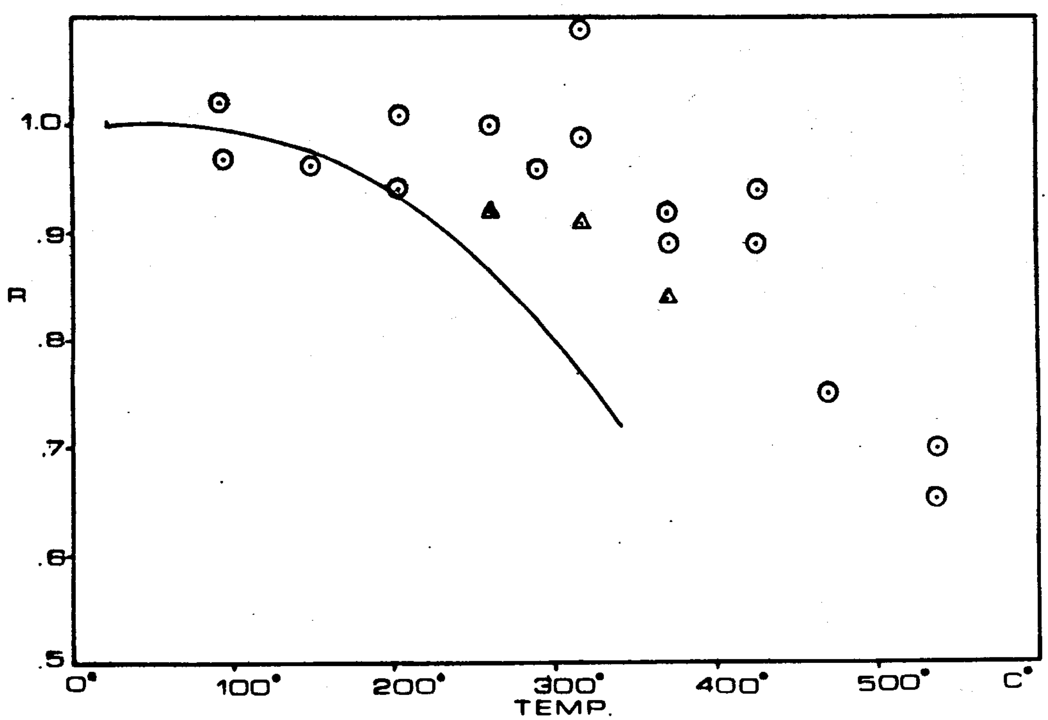

Fig. 4 - Values of ratio "R" between yield stress of the N 80 steel at high temperatures and the value setted to am bient temperature.